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HEADQUARTERS QUARTERMASTER RESEARCH & ENGINEERING COMMAND

Quartermaster Research & Engineering Center, U.S. Army

Natick, Massachusetts

ok TEXTILE, CLOTHING AND FOOTWEAR DIVISION

Textile Engineering Laboratory Report No. 266

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SIMULATION OF SWEATING INTO CLOTHING WITH CONSTANT SKIN TEMPERATURE

by

Lyman Fourt

Project Reference
7-93-18-020A

1960

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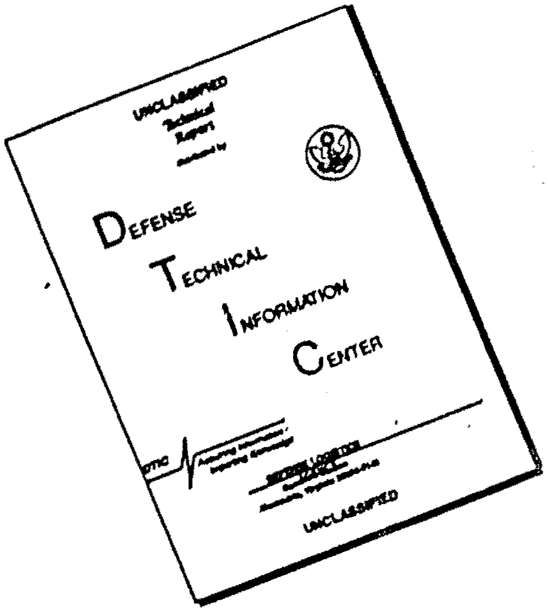

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FOREWORD

e deals with

Th~~is~~ ~~is one of a series of~~ report~~s~~ ~~in~~ the general field of wool type fabrics and alternates to conserve wool, with special reference to the physical features by which clothing structures contribute to the protection and effectiveness of the soldier.

This report was prepared by Harris Research Laboratories under Contract No. DA 19-129 QM 1336, Headquarters Quartermaster Research and Engineering Command, Quartermaster Research and Engineering Center, U.S. Army, Natick, Massachusetts. The contract, entitled "Investigation of Properties of Synthetic Fibers in Blends with Wool," was initiated under Project No. 6-93-18-2-, Development of Alternate Fabrics to Conserve Wool: Task: Development of principles to improve the insulating characteristics and "comfort" of textile fabrics combinations, and was administered under the direction of the Textile, Clothing and Footwear Division, Headquarters Quartermaster Research and Development Center with Mr. Constantin J. Monego acting as project leader.

This material is contractor's Report No. 33, for the quarter ending Sept. 11, 1959, the third quarter of this contract.

INVESTIGATION OF PROPERTIES OF SYNTHETIC
FIBER IN BLENDS WITH WOOL

Contract No. DA-19-129-QM 1336
O.I. No. 9075
Third Quarter
Period ending Sept. 11, 1959

HARRIS RESEARCH LABORATORIES, INC.
6220 Kansas Avenue, N. E.
Washington 11, D. C.

Contractor's Report No. 33

SIMULATION OF SWEATING INTO CLOTHING WITH CONSTANT SKIN TEMPERATURE

* * * * * *

SUMMARY

An improved simulation of sweating into clothing ~~is~~ was obtained by maintaining constant skin temperature by means of an automatically regulating power supply. ~~As in the previous report~~, an impermeable film, which can be removed without disturbing the clothing assembly, permits establishment of a steady temperature gradient in dry clothing, followed by the sweating process.

With constant skin temperature, there is an initial pulse of temperature rise in the clothing at the start of sweating, followed by cooling to a new steady state in which the clothing temperatures are higher than in the dry condition.

The power increases at the start of the period of sweating, and quickly becomes constant at a higher level before the temperatures have reached new steady values. The new constant rate can be used to calculate the ratio

of combined heat loss through the clothing during sweating to the loss through dry clothing without sweating, or an equivalent thermal resistance for the clothing during sweating. The equivalent resistance with sweating is about 50 percent of the dry resistance, for wool serge, polyurethane foam and polyester fiber batt. Differences between these types of material in the ratio of equivalent resistance to dry resistance are much smaller than the difference caused by sweating in any one material. Although these materials are approximately similar in decrease of resistance while sweating is going on, they differ considerably in amount of water retained, with less retained by low density, low regain materials. This retained or accumulated water is important with respect to chill after heavy work and sweating, since it continues to evaporate after the man has ceased to sweat.

FF-p17 The chief suggestion for improvement of clothing arising from this work is to reduce the amount of water accumulating in the clothing, by such means as lower density or use of lower regain fibers.

EXPERIMENTAL METHOD

A brass cylinder, two inches in diameter, and wind tunnel with air stream at 5 mph, were used, all in the cold box at about -3° C. air temperature, as in earlier reports.

Surface temperature controller:

A resistance wire grid on the evaporating surface of the test cylinder is used as one arm of a Wheatstone bridge, with a sensitive relay to detect off-balance. This relay, in which latching force is dependent not merely on the activating current, but also on magnets, is reset to center at intervals of about 7 seconds by an interrogating circuit. If power continues to be needed, it goes on again until the next interrogation, but if power is not needed, it will stay off, in center position, or go to the other pole.

Power Measurement:

The power supplied to the test cell was measured in two different ways, in different tests. In one, the "on" side of the relay was connected to a timer, so that the time on could be cumulated. This, with voltage and current, measured power supply. In the other method, a watt-hour meter was modified with a photoelectric counter to count the revolutions of the disc. This also could be used to cumulate the power supply in arbitrary units, and by calibration, in units of energy.

With each method of measuring power, the interrogation period provided a brief pause in which the instruments could be read. Charts of increments at various intervals, from 7 seconds, the base period, up could be made: a period of 5 minutes was found suitable for a smoothed average.

Initiation of sweating:

The system of starting sweating into the natural thermal gradient set up in dry clothing, by removing an impermeable layer made of polyester film, as described in Report 32, was continued. In most of these tests, this was done in the same way as in Report 32, by removing one of the end insulating blocks, pulling out the film, and replacing the block. This, however, may chill the test cell, and interfere with observations of power requirement close to the start of sweating.

In order to observe the start of sweating more closely, the end insulation was revised, as shown in Figure 1, to a doughnut like block, fitting over insulation cemented to the end of the brass cell. The polyester film could thus be drawn out between the doughnut and the center, with minimum disturbance of the clothing or exposure of the end of the cell.

A layer of vapor permeable cellophane was used between the wet chamois and the outer layers, just interior to the polyester film, and was left in place to limit moisture transfer to evaporation.

RESULTS

Typical temperature sequence:

Temperature was followed at three levels in the clothing, in these tests, instead of at two, as in Report 32, by resistance wire grids carried on polyester fiber fabrics. The arrangement of layers is diagrammed in Figure 2. The same general sequence, of a quick temperature rise in the clothing, followed by a slower cooling to a new steady state, is seen. The greatest range of change, however, is in the center of the clothing layers.

The inner layer remains close to the controlled surface temperature. One reason that the outer layer response is reduced in most of the examples in this report is that rather large thicknesses were used.

The final steady state temperatures in the present constant surface temperature tests are higher than in the dry fabrics, not lower as they were with the constant power tests of Report 32.

Variation with materials:

Figures 3 and 4 show results for 2 and 8 layers of wool serge, while Figure 5 shows 2 layers of polyester foam, and Figures 6 and 7 show polyester fiber batt, in two densities. Corresponding numerical data are in Table 1. All follow the general pattern just described, but it can be seen that the wool layers are slower in reaching the peak, and show more rounding of the peak of temperature and slower cooling, than the less absorbent foam and polyester fiber. The change with thickness is greater for wool fiber also.

Water accumulation:

The effect of time on the accumulation of water was not examined but the result found for constant power conditions, that water continues to accumulate as sweating goes on, has been used to adjust observations somewhat longer or shorter than 60 minutes, on the basis of proportionality to time. The amounts accumulated, on a 60 minute basis, are shown in Table 2, as grams per square meter of evaporating surface. The grams per square meter of clothing are smaller, since the clothing surface increases with increasing radius.

The weighings involved in determining water losses and water contents vary in the degree to which they are affected by evaporation losses during the weighing period itself. The initial dry weights of clothing can be determined accurately, and the initial weight of the assembly, because evaporation is prevented by the impermeable film. The final weight of the whole assembly is also relatively accurate, since it is obtained immediately after the end of the test period. The weights of the impermeable film and the water removed on its inner surface are also obtained immediately, so the net loss from the whole assembly can be established relatively accurately.

The layers themselves are weighed quickly, as they are unwrapped from the assembly, but there are some losses by evaporation during this process. Hence the weights of water accumulated in the clothing are minimum values. Since the wet cell is weighed last, the evaporation from the skin is probably a maximum value. The difference between loss from the system as a whole, and loss from the skin, is always larger than the accumulation in clothing and grid layers, leaving some water not accounted for. In the presentation of results in Table 2, these maximum and minimum relations are indicated.

Table 2 shows that the evaporation from the skin is in every case larger than the evaporation from the system as a whole. With two and eight thicknesses of wool, the evaporation from the skin was practically the same in each, but more escaped from the system as a whole with the thinner cover. The tests with low regain systems were with thicker assemblies than the wool, so that greater thickness may account for the lower evaporation from the skin, but the low regain and low density appear to be connected with the greater net evaporation from the system.

The accumulation of moisture in the clothing also appears related to regain, much more being retained by the wool layers than by the other materials. A possible additional effect, operating in the same direction as the higher regain of the wool, is the greater amount of fiber, and greater surface area, involved in wool fabrics as opposed to small amounts of polyester fiber in batt form. However, the firm polyester batt has nearly the same weight as the lesser thickness of wool, but retains much less water.

Comparison of evaporation and power supply:

The amount evaporated per hour can be expressed as the corresponding power in watts, and compared with the power supplied, in steady state dry or wet. The power supply has been corrected for end losses, by the calibrations of Report 31. The power supply figures are shown for tests made with the on time method of measuring power. Qualitatively similar results were obtained with the watt hour meter, but lack of calibration steps involving power losses in intermediate transformers prevents direct comparison.

Comparing the increase in power due to sweating with the calculated power for evaporation, as shown in Table 2, one sees that the increase in overall power due to sweating is intermediate between the evaporation at the skin level and the evaporation from the system as a whole. This indicates, as was discussed in Report 32, that there is no clearcut separation into parallel processes of energy transfer by heat and by moisture, simultaneously but separately. Rather, there is a progressive interchange between energy transfer by evaporation, which is greatest at the skin, and energy transfer as sensible heat, which is augmented within the clothing by the condensation of water.

Effect of start of sweating on power requirement:

The on-off characteristics of the regulating system, and variability and overshooting, prevent as detailed an approach to power measurement as was hoped for. However, as nearly as one can tell from five minute averages of power requirement, the power goes at once to a new level, when sweating is started at constant skin temperature, and continues at this level for a long time, through the cooling part of the transient temperature effect and into the steady temperature period as far as we have followed it. The power supply rate, for five minute intervals, is shown in Figure 6, in which one can also see how an excess of power in one interval produced an upward wave of temperature in all layers.

Combined heat loss ratio:

The power required to maintain the skin at constant temperature, corrected for losses through the ends in order to obtain the power flowing through the sides, is a measure of the combined heat loss rate by all mechanisms. The ratio, (power with sweating)/(power dry) gives the increase of heat flow by all mechanisms, with sweating. This ranges from 1.5 times as much combined loss for sweating through wool, to 2.4 for a polyester batt.

Equivalent resistance during sweating:

Since the power becomes and remains constant, while sweating is going on, and while water is accumulating in the clothing, it is possible to calculate an equivalent resistance during sweating, in analogy to the thermal resistance under dry conditions. This equivalent resistance, Req, is:

$$Req = \frac{(T_i' - T_o')\,A}{W_s'}$$

where T_i' and T_o' are the temperatures on the two surfaces of the clothing in the steady condition, with sweating, W_s' is the watts dissipated through the sides of the test cylinder while sweating is going on and A is the area. We can concentrate our attention on the effect of sweating by considering the ratio of equivalent resistance with sweating to dry resistance. This ratio is:

$$Req/R = \frac{(T_i'-T_o')}{W_s'} \; \frac{W_s}{(T_i-T_o)}$$

where the primes refer to steady conditions with sweating, and the corresponding symbols without primes refer to the dry condition. These temperature differences and the ratios of clothing resistance are shown at the bottom of Table 2, for the constant skin temperature series.

Since the saturation vapor pressure changes more rapidly than the temperature, one might expect a shift between the relative effects of vapor and direct heat transfer, with change of skin temperature. The method of test described in Report 32, in which power was kept constant and skin temperature was allowed to reach its own level, provides data at a range of lower temperatures. Table 3 lists the skin temperatures, the temperature differences in the clothing, and the power dissipated through the sides, and Figure 8 plots the ratio of equivalent resistance while sweating to dry resistance, against skin temperature.

The data in Figure 8 show considerable scatter, and any trend with surface temperature is small, in this range. A trend toward lower equivalent resistance while sweating, relative to resistance while dry, would be expected, for increase in skin temperature. The fact that any trend is small in this

range of temperature permits use of the equivalent resistance while sweating, or the ratio of this to dry resistance, as a characteristic of a clothing assembly.

The scatter of the data available is such as to suggest that all of the materials tested are similar, in undergoing a 50 percent loss of resistance to energy transfer, during sweating. This change is larger than any differences between the materials with respect to the amount of change.

DISCUSSION

Relation to clothing in use:

In the actual use of clothing, the dry condition, as used in these tests, corresponds well with clothing freshly put on, and more or less with clothing in constant wear without a period of high exertion and sweating. There will be some insensible perspiration from the cool dry skin into the clothing, but the changes due to this are probably small compared with the changes due to water vapor from a warm, wet skin. The prior effect of insensible perspiration may, however, take some of the peak off of the start of sweating.

If exercise increases heat production above what can be dissipated down the thermal gradient, sweating will begin, and conditions will correspond to the sweating portion of the tests. Any given relatively thick assembly will approximately double its heat dissipating rate, and continue to let energy be transferred at some fixed rate, by a combination of vapor and direct thermal transfer, while water accumulates in the clothing. For thick clothing assemblies, this rate is independent of the water content over a wide range.

With lower activity after a high level of work and sweating, sweating from the skin will cease and skin temperature will fall. The water content of the clothing will then be the critical factor. Until the inner layers of f[illegible] have become dry, the vapor mechanism of energy transfer will be operative, adding to the heat drain.

Suggestions for improvement of clothing:

The chief suggestion for improvement of clothing for cold environments ari[illegible] from this work is to reduce the accumulation of water in the clothing. This may be accomplished in several ways. With a given material, an impermeable membrane with spaced holes to permit vapor escape through only part of the area may reduce the accumulation of water more than it reduces the escape of water vapor, as suggested in Report 18 of this series.

One can also reduce the accumulation of water by using material of lower regain, if thickness can be kept at the same level. One can probably gain by using structures such as batts or foams, which have lower density and less material and fiber surface area for a given thickness than conventional [illegible] fabrics. However, the other requirements of use and garment design are involved in the substitution of batts or foams for woven fabrics.

TABLE 1

COMPARISON OF MATERIALS AND TEMPERATURES

Material:	Wool Serge	Wool Serge	Polyurethane Foam	Polyester Fiber Firm Batt	Polyester Fiber Light Batt
Radial thickness, cm	0.50	2.07	2.30	2.54	2.47
Density, g/cm^3	0.21	0.23	0.027	0.036	0.012
Temperature in center					
Dry, steady, °C.	18.0	13.2	13.3	11.3	11.6
Peak, °C.	26.9	20.8	19.2	17.0	16.4
Final, steady, °C.	20.4	17.2	15.8	15.0	14.0
Peak rise, °C.	8.9	7.6	5.9	5.7	4.8
Time to peak, min.	2.0	7.5	2.0	2.0	1.5

TABLE 2

EVAPORATION AND ACCUMULATION OF WATER, OBSERVED OR CALCULATED IN PROPORTION TO TIME, FOR 60 MINUTE PERIOD. AREA BASE IS THE EVAPORATING SURFACE

Materials:	Wool Serge	Wool Serge	Polyurethane Foam	Polyester Fiber Firm Batt	Polyester Fiber Light Batt
Radial thickness, cm	0.50	2.07	2.[illegible]	2.54	2.47
Length of sweating, min.	76	41	61	60	60
Dry material,					
inner layers, g/m^2	430	2070	270	340	120
outer layers, g/m^2	550	2[illegible]00	310	510	160
Evaporation from skin, maximum, g/m^2	265	268	176	140	194
Net evaporation from system, g/m^2	69	56	75	59	102
Accumulation, minimum					
inner layers, g/m^2	59	130	4	10	18
outer layers, g/m^2	43	71	21	19	11
inner layers, %	14	6	1.5	3	15
outer layers, %	8	3	7	4	7
Power equivalent of evaporation					
at skin watts/m^2	178	180	118	94	131
from system watts/m^2	46	38	50	40	69
Power supply to sides (steady conditions)					
dry, watts/m^2	155		66	46	
sweating, watts/m^2	235		137	111	
increase, watts/m^2	80		71	65	
Power ratio, sweating/dry	1.5[illegible]		2.08	2.44	
Temperature difference across clothing					
sweating, °C.	17.5		25.3	24.9	
dry, °C.	19.7		26.8	28.3	
Clothing resistance ratio, equiv. sweating/dry, %	59		45	36	

TABLE 3

EQUIVALENT RESISTANCE OF WHOLE FLOW OF ENERGY IN STEADY STATE WITH SWEATING, COMPARED WITH DRY THERMAL RESISTANCE, FOR TESTS WITH CONSTANT POWER SUPPLY. (OTHER FEATURES OF THESE TESTS ARE IN REPORT 32.)

Material	Radial Thickness cm	Skin Temperature, Sweating °C.	Temperature Difference through clothing: Dry °C.	Temperature Difference through clothing: Sweating °C.	Power through sides: Dry watts/m²	Power through sides: Sweating watts/m²	Resistance Ratio Sweating/Dry %
Wool serge	0.27	22.2	9.4	7.0	166	186	66
	0.95	24.8	23.3	13.4	88.5	105	48
Polyester fiber batt	0.49	21.1	15.1	8.9	131	154	50
	0.48	20.2	20.4	12.7	149	175	53
Polyurethane foam	0.35	21.5	10.6	7.1	140	167	50
	0.36	20.0	12.3	7.6	136	162	52
	0.36	20.8	16.3	[illegible]	164	188	56
	0.46	20.7	22.8	15.8	162	179	63
	0.46	20.6	18.8	11.4	165	181	55
	0.48	21.1	17.5	10.9	118	141	52
	0.76	21.6	17.6	10.8	101	123	50
	0.82	23.6	23.1	17.4	98	115	64
	0.89	22.8	17.6	11.5	97	115	55
	1.04	22.0	25.3	17.2	98	118	56

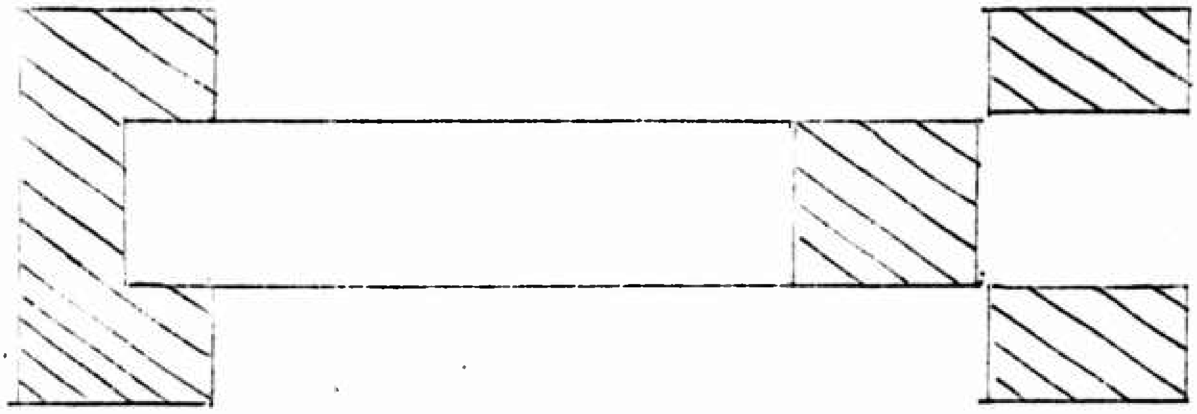

Figure 1, Report 33.

Arrangement of test cylinder and insulated ends, to permit start of sweating by pulling an impermeable film out through the "hole in the doughnut" at the right, without disturbing the clothing or exposing the end of the cylinder.

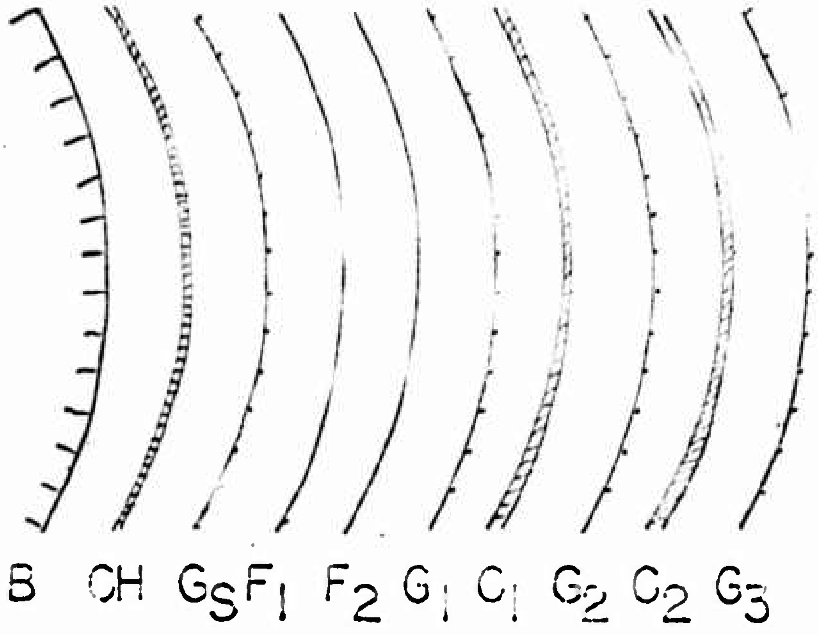

Figure 2, Report 33.

Sequence of layers on side of test cylinder, with space between layers exaggerated.

B is the brass shell

CH Chamois

G_s Grids for surface temperature and temperature control

F_1 Film of vapor permeable cellophane

F_2 Removable impermeable polyester film

G_1 G_2 G_3 Inner, middle, and outer temperature measuring grids on polyester fabric

C_1, C_2 Clothing layers.

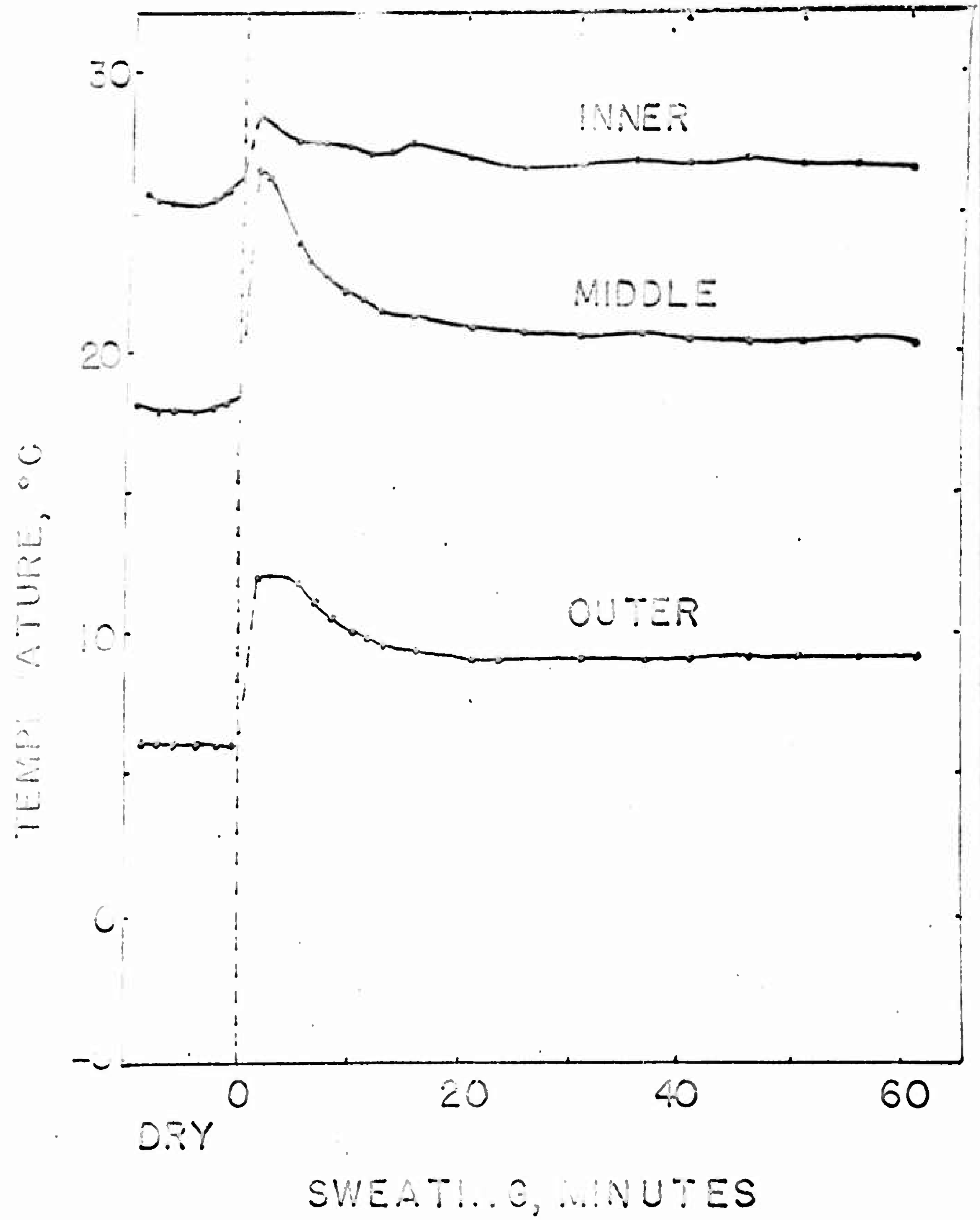

Figure 3, Report 33.

Temperature sequence, with two layers of wool serge, radial thickness 0.50 cm.

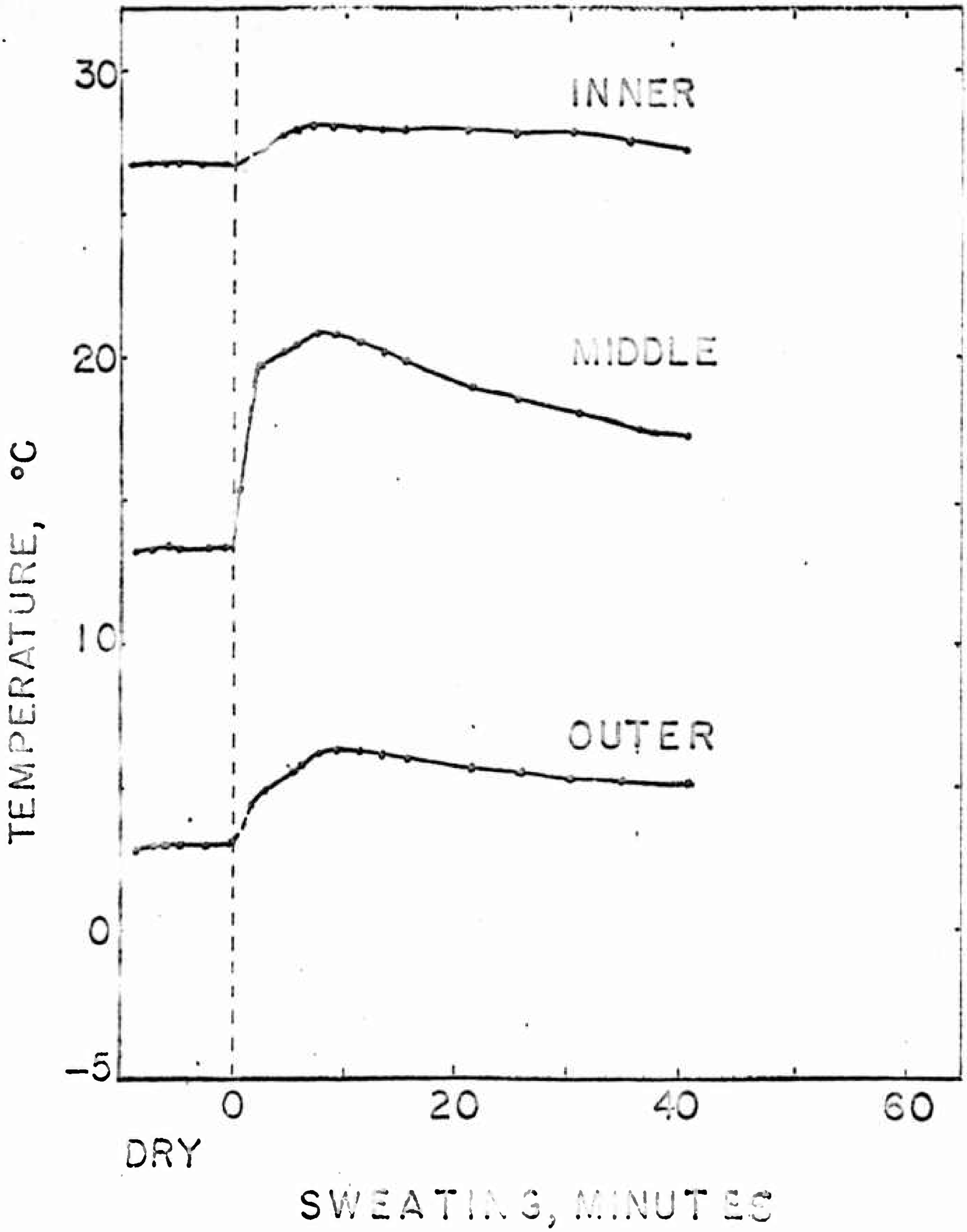

Figure , Report 33.

Temperature sequence with 8 layers of wool serge, radial thickness 2.07 cm.

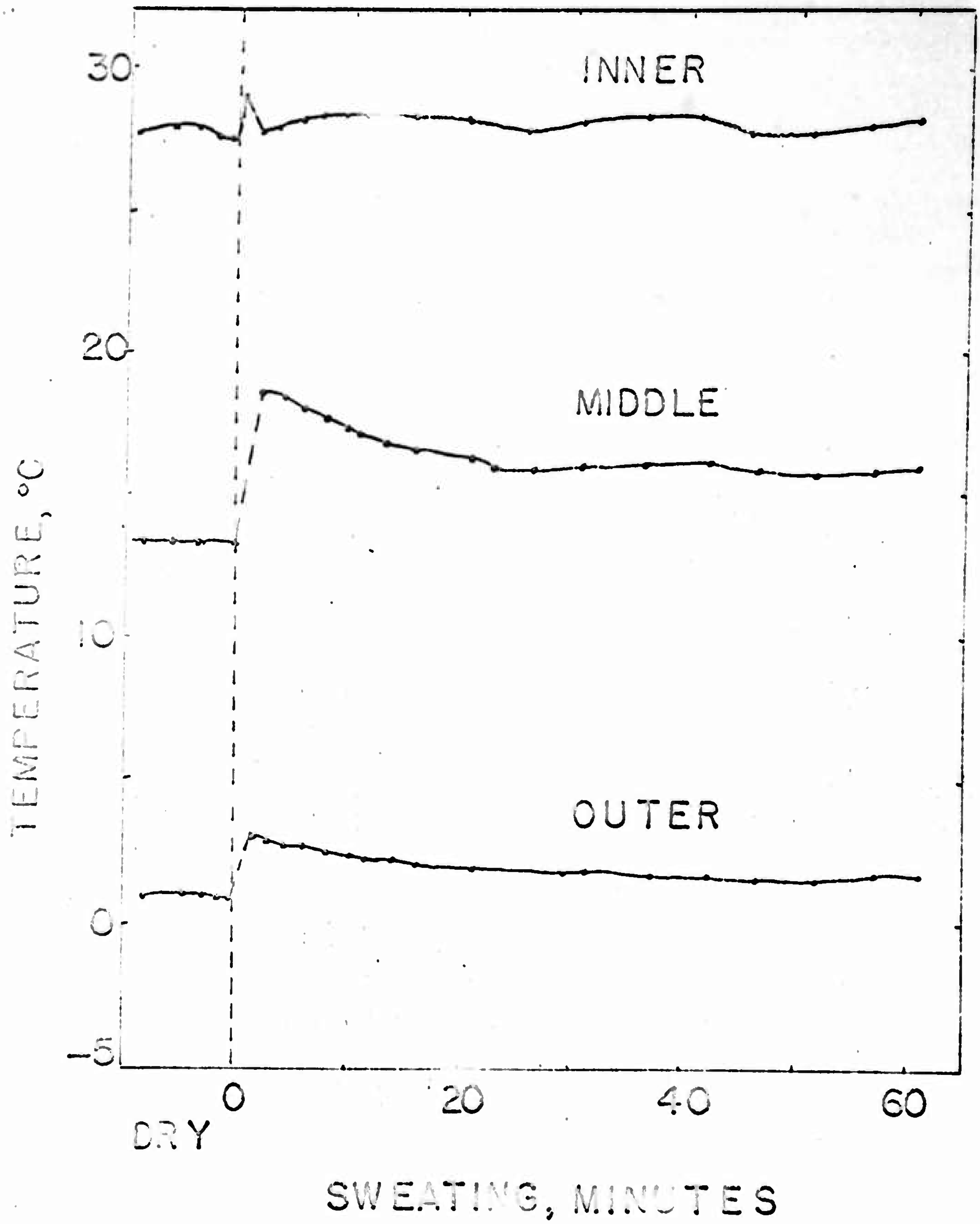

Figure 5, Report 33.

Temperature sequence with polyurethane foam, radial thickness 2.30 cm.

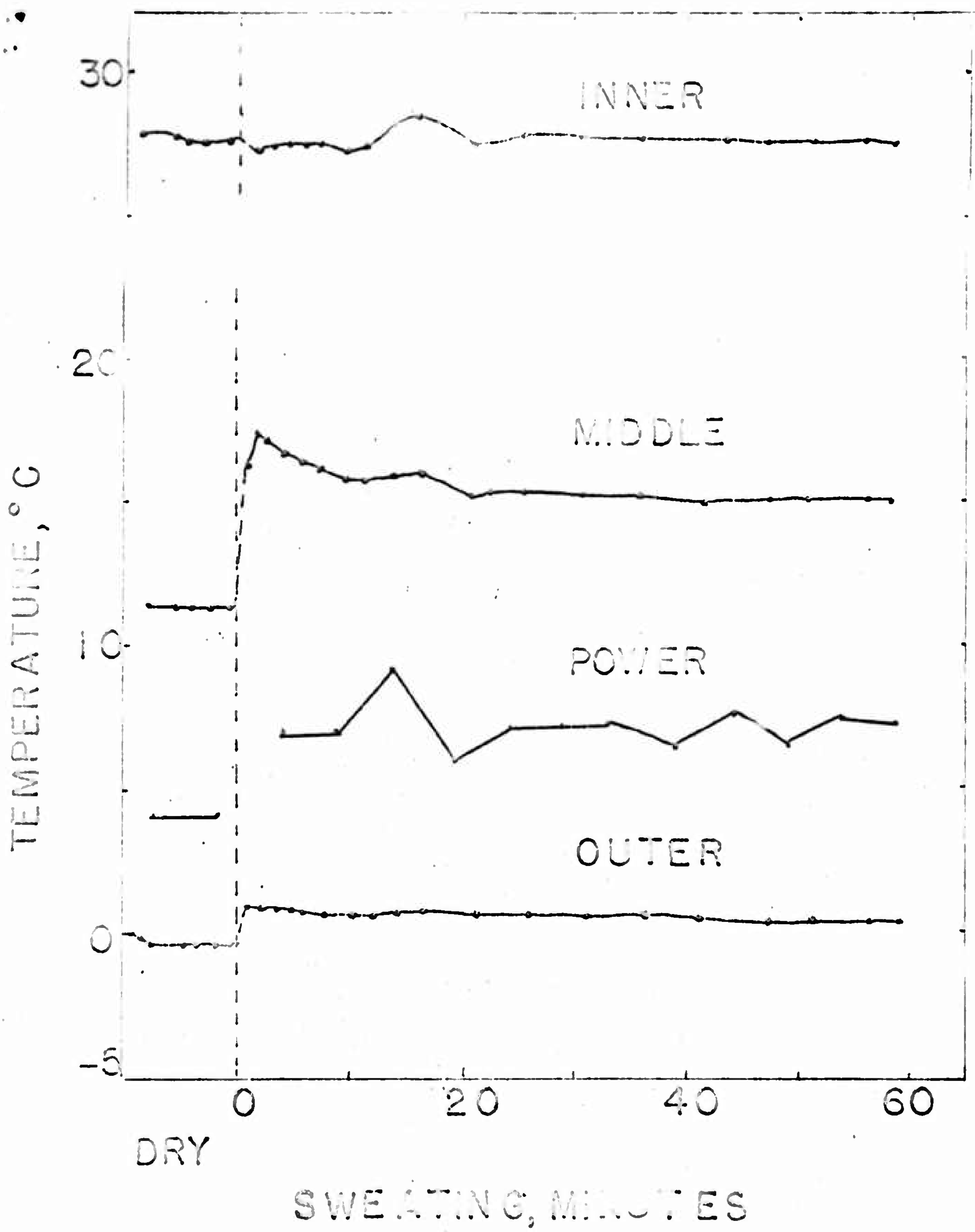

Figure 6, Report 33.

Temperature sequence with polyester fiber batt, density 0.036 g/cm^3, radial thickness 2.54 cm. The power supply, averaged for 5 minute periods, is also shown (same scale for watts and temperature). An excess of power at 15 minutes shows as a wave in the temperature sequences.

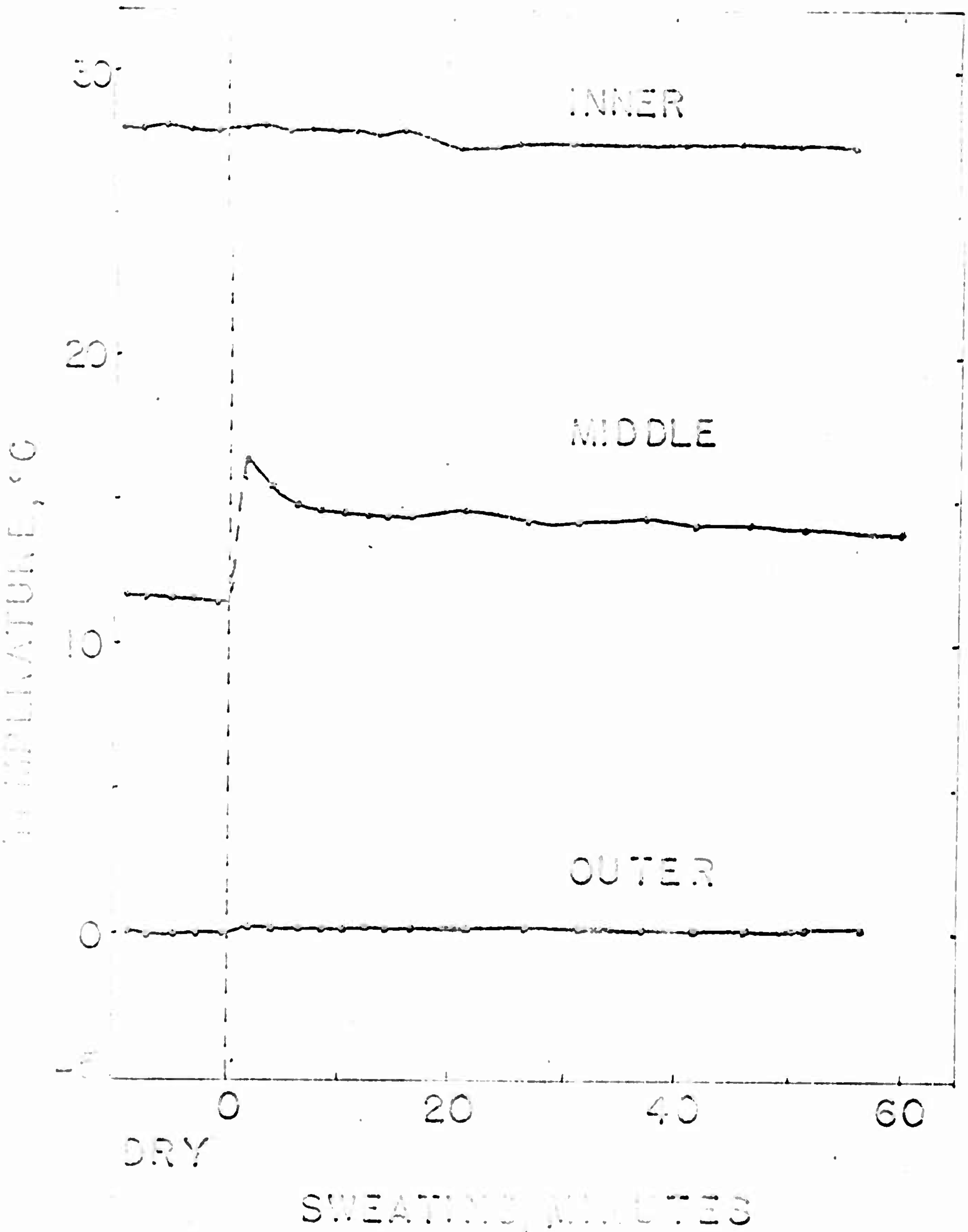

Figure 7, Report 33.

Temperature sequence with polyester fiber batt, density 0.012 g/cm^3, radial thickness 2.47 cm.

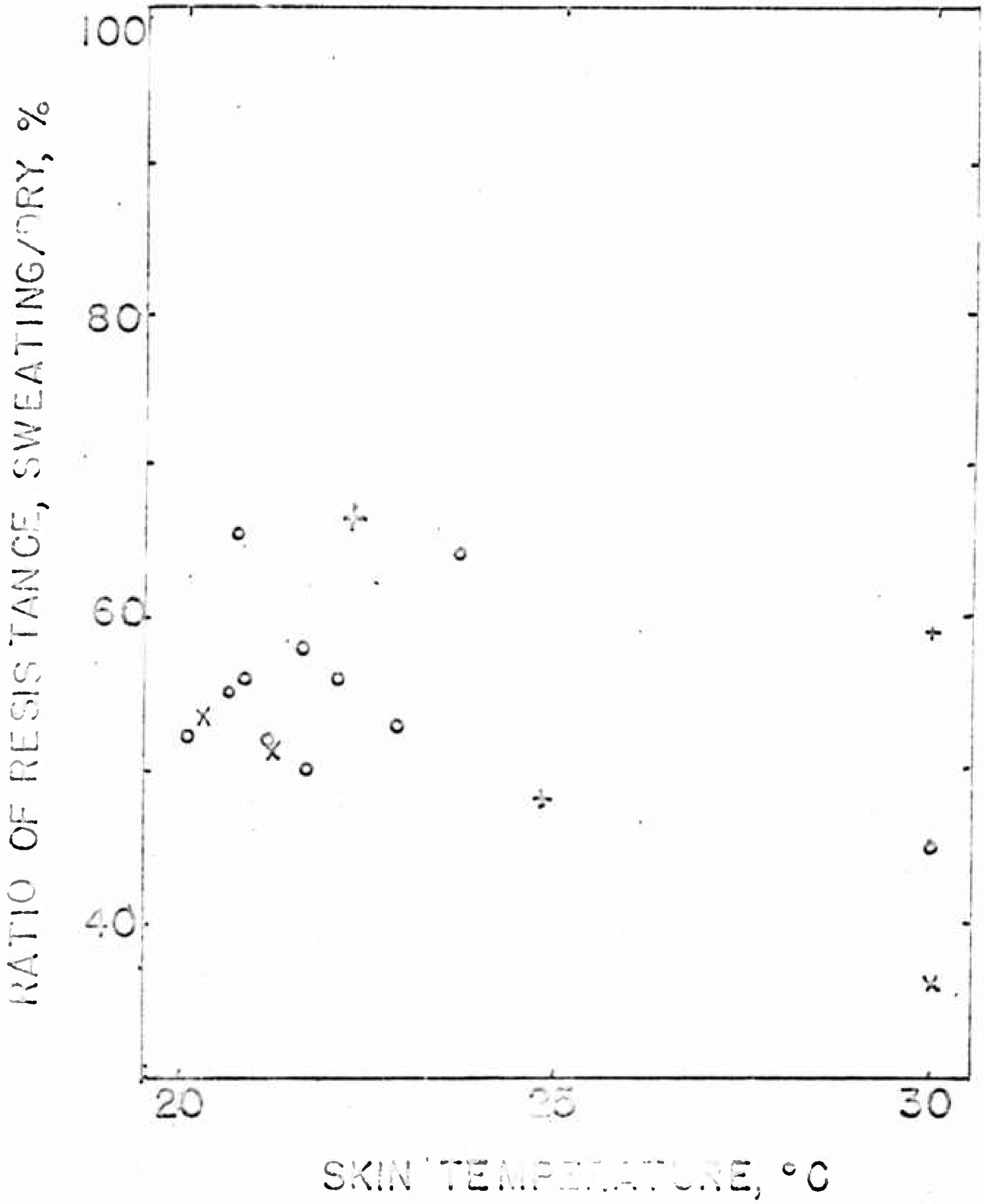

Figure 8, Report [illegible].

Ratio of equivalent resistance while sweating to dry resistance, for a range of thicknesses of [illegible] and corresponding skin temperatures. Open circles indicate polyurethane foam; crosses, wool serge, x's, polyester fiber batts.